FAR-INFRARED FOCAL-PLANE ARRAYS

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ABSTRACT

A project to develop a far-infrared detector array using II-VI material technology is described. The eventual goal is the production of a 32×32 element HgCdTe array for the 40-63 μm wavelength band.

INTRODUCTION

The introduction of large 1000×1000-element arrays at near- and mid-IR wavelengths has dramatically enhanced the science capabilities of ground- and space-based telescopes. The question naturally arises whether similar arrays can be built for longer wavelengths ($\lambda > 40$ μm); and, if so, what are the best technologies to pursue. Currently, the largest FIR array is the 50-95 μm MIPS array built for SIRTF. This 32×32 element Ga:Ge array is built with discrete detectors with mm-scale absorption lengths. The technology, though very sensitive, will be difficult to scale to larger sizes, although a similar 64×64 element array is now being developed[1]. Even larger arrays will require a planar technology in which the detectors can be defined lithographically. Fortunately, there are several promising technologies.

The first is an extension of extrinsic detector technology, but with doping densities 100 times higher. Ga:Ge doped at 10^{16} cm^{-3} has an absorption strength of 100 cm^{-1}, and so detectors only 10 μm thick can have good quantum efficiencies. Impurity band conduction is blocked by an undoped layer, and hence these devices are called IBC or BIB detectors[2]. This technology appears most promising for the 70-200 μm band, but the devices will need to be cooled to ≤ 2K. The second planar technology involves the creation of quantum-well structures in III-V materials such as InAs/GaSb and others[3]. The quantum well devices will have absorption strengths of 100 cm^{-1} in the 10-70 μm band, and a relaxed cooling requirement of about 10 K. Theoretically, one could also make zero-band-gap III-V alloys (i.e., InTlP, InTlAs, or InTlSb), but these materials have been difficult to fabricate epitaxially. The third approach is the one favored here. It involves the II-VI group materials HgTe and CdTe, which can be used effectively in either zero-gap alloys or multiple-quantum-well structures. Most near-IR arrays are made with HgCdTe alloys, and in fact over 10^8 pixels have already been delivered by industry. This major investment by the industrial sector favors II-VI materials for either large-scale or mass-produced FIR arrays, should the technology prove applicable. Our mission is to demonstrate that II-VI technology is applicable, initially in the 40-63 μm spectral region. Our NASA-sponsored program has 3 near-term goals: (1) to fabricate discrete alloy and superlattice (SL) photoconductors, (2) to fabricate SL photodiodes, and (3) to fabricate a 32x32 element array.

To speak of FIR planar arrays brings up the question: *ultimately, how big* ? The pixel size is set by optical coupling requirements, and should be at least 4λ at the operating wavelength. Consequently, a 1000×1000 element array for $\lambda = 100$ μm would need to be 40×40 cm in size. Well, that's a bit ambitious. By scaling down expectations to a 256×256 element array, and by using a silicon immersion lens for optical coupling, we can reduce the array dimensions to 3×3 cm, which is consistent with the current state-of-the-art. The smaller pixel size of 120 μm in this latter array has the added advantage of reducing the dark current and the cosmic ray susceptibility by factors of 10.

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MATERIALS: BAND-GAP ENGINEERING

Two approaches are available for fabricating II-VI materials with the 10 meV bandgaps needed for $\lambda = 100$ μm applications. The first is the well-known alloy approach in which the bandgap is tailored by varying the mole fraction *x* of CdTe in a HgCdTe alloy. This is the method used to fabricate all HgCdTe arrays to date. The second approach relies on the creation of a multiple quantum well structure called a superlattice (SL), in which HgTe (well) layers and CdTe (barrier) layers are alternated repeatedly. The bandgap of this composite structure is set primarily by the thickness of the well layer (HgTe). Absorption coefficients $\alpha > 100$ cm^{-1} are readily achieved with these materials at FIR wavelengths, and so a superlattice thickness of 10 μm should yield a 10% quantum efficiency (single pass). There appears to be no fundamental reason why 256×256 arrays of HgCdTe detectors could not be made for the λ=40-70 μm wavelength region. (NOTE: HgCdTe has a lattice absorption band at λ=70-90 μm.) However, as the bandgap is reduced to near zero, we must become more concerned with tunneling currents, and so it remains to be seen whether BLIP sensitivity can be achieved at the low backgrounds expected in space. On the other hand, at the higher backgrounds expected on SOFIA, or for space-based observations of planetary atmospheres[4], BLIP sensitivity should be possible.

$Hg_{1-x}Cd_xTe$ Alloys

At 77 K, the band gap of the semimetal HgTe is –0.26 eV, and that of the semiconductor CdTe is 1.6 eV. These materials can be alloyed using various Cd fractions *x* to tune the bandgap E_g(eV) of $Hg_{1-x}Cd_xTe$ to intermediate values (including zero)[5].

Figure 1 shows the cut-off wavelength, defined as $\lambda_{co}(\mu m)=1.24/E_g(eV)$, as a function of temperature for various fractional compositions *x* . It is evident that by choosing *x* between 0.16 and 0.17, a wide range of cut-off wavelengths in the FIR can be obtained. For the approximate 0.01 eV band gap needed for 100 μm response, *x* would be close to 0.17. As the band gap approaches zero, small fractional changes in *x* lead to large fractional changes in the gap energy, and generally we need to control *x* to within 0.2% to have a 10% uncertainty in peak response. It should be apparent that compositional gradients could lead to variations in the gap and thus a non-uniform response across an array detector. Nevertheless, we believe that by using molecular-beam-epitaxy (MBE), adequate composition control is available. As a test of this control, n-type alloy material with x=0.165 was successfully fabricated on silicon substrates.

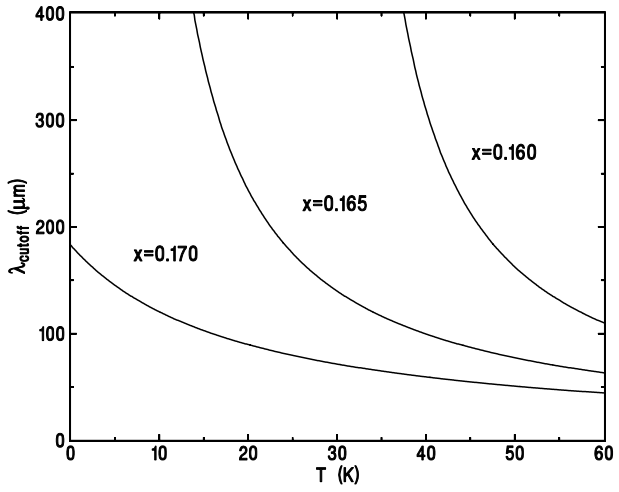

Fig. 1: *The cut-off wavelength is plotted against operating temperature for various Cd fractions x.*

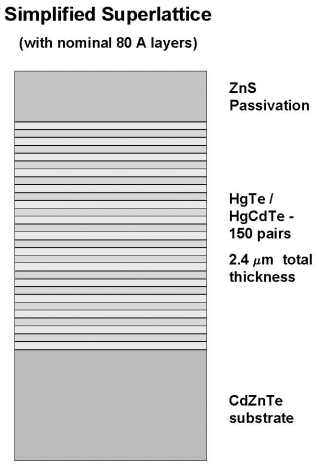

Fig. 2: *Schematic diagram of a superlattice photoconductor.*

Superlattices

A superlattice (SL) is a composite semiconductor consisting of a large number of alternating well and barrier layers – hence multiple quantum wells. Figure 2 shows a schematic cross-sectional view of a SL structure. The thickness of the SL in the growth direction is typically 3-10 μm. The lateral size of the SL should appear to be at least 4 λ, so that simple optical coupling can be used (note that Fig. 2 is not to scale.)

For detector applications, superlattices have a number of advantages over alloy semiconductors:

(a) the bandgap is easier to control because it depends on layer thickness rather than composition,

(b) the large effective masses of electrons and holes in the growth direction lead to an order of magnitude (or more) reduction in tunneling currents,

(c) carrier degeneracy effects (conduction band filling) near the long-λ band edge are less significant, and

(d) a superlattice can suppress Auger recombination by intentionally inducing strain.

The required thicknesses for the well (d_w) and barrier (d_b) layers of a SL are determined from band structure calculations, but can be summarized as follows. The band gap of a HgTe/CdTe superlattice depends almost entirely on the HgTe well thickness (d_w), because the barrier height of CdTe (or that of the $Hg_{0.05}Cd_{0.95}Te$ used here), is much greater than the well depth of HgTe. When d_w is < 6 nm, the SL is a semiconductor with a normal band structure. At approximately 6 nm the band gap is zero. When d_w > 6 nm, the SL is once again a semiconductor; however, the band structure is now inverted (i.e., the H1 subband is now the conduction band). Noteworthy is the very weak dependence of E_g on the HgTe width. At T=4 K E_g is zero when d_w = 6 nm, increases to 28 meV when d_w = 8 nm, and gradually decreases to 15 meV when d_w = 15 nm. We chose to maximize E_g for our first try, and fabricated SL material with d_w = 8 nm, d_b = 7.7 nm, and hence $\lambda_c = 1.24/E_g$ = 44 μm.

Measured Hall mobilities for the fabricated materials were excellent, about $3x10^4$ $cm^2/V{\cdot}s$ at T = 300 K, increasing to 1.5 x 10^5 $cm^2/V{\cdot}s$ at T = 50 K. TEM microscopy revealed good definition between layers and no evidence for significant Hg interdiffusion at the MBE growth temperature of 180 K.

FABRICATED DEVICES

Photoconductors

Alloy material with x=0.165 was used to fabricate test photoconductors with 300 μm × 300 μm size. SL photoconductive devices of similar dimensions were also fabricated. These detectors are now being packaged for optical tests at FIR wavelengths. It should be noted that the material was grown as n-type, which is necessary should we wish to subsequently process the material into a p-on-n photodiode device. N-type material, however, is not ideal for a purely photoconductive (PC) detector, because of its higher dark current compared to p-type material (μ_{hole} = 1/200 μ_e for HgCdTe). N-type material is also affected adversely by conduction band filling problems (Burnstein-Moss effect) that render the device transparent at long wavelengths near the band edge.

Alloy devices should be good for high-speed detectors and heterodyne mixers. By using interdigitated surface electrodes with a 20-40 μm electrode spacing, transit times can be short enough that IF bandwidths of several GHz are achievable[6]. We are now fabricating masks for a small 6-element linear array of alloy HgCdTe photoconductive mixers for the 50-120 μm spectral band.

Photodiodes

Large arrays of detectors require a multiplexed readout. Because of the small "well depths" (*i.e*, limited capacitor size) of the read-out-integrated-circuit (ROIC), a large detector resistance is preferred. A reverse- or zero-biased photodiode device structure helps in this regard. Both the alloy and superlattice materials described above can be processed into photodiodes by the addition of a p-type layer onto the n-type material. The method currently favored for p-on-n is As-doping via ion implantation, although *in situ* As doping during MBE material growth has also been used successfully. Arsenic is favored here because of its relatively low thermal diffusion constant in HgCdTe. However, the As must be "activated" to occupy a Te site in the lattice if it is to function as an acceptor. This activation is readily accomplished by thermal annealing at T = 250-300 °C for 30-180 min. Although this annealing process generally causes no serious harm to alloy material, it is problematic for a SL which is itself grown at T=150-180 °C. To address these concerns we ran a series of annealing experiments on different batches of SL materials. As expected, the 250 °C anneal for 30-min caused noticeable interdiffusion between the SL layers, so much so that Hall mobilities dropped by a factor of 50 and the mid-IR absorption of the SL departed significantly from that measured for as-grown material. So now we must consider several alternative methods which are available for p-on-n (and n-on-p) junction fabrication.

RESULTS

The first year effort has produced the following results:

(1) HgCdTe alloy material has been grown via MBE with x=0.165, corresponding to a calculated λ_c = 200 μm at T=20 K.

(2) HgTe/HgCdTe superlattice material has been grown via MBE with 150 layer pairs and λ_c = 50 μm. The optical and electrical properties of the as-grown material were verified to be good via TEM X-ray diffraction and Hall measurements. Annealing tests were completed.

(3) Photoconductive detectors were fabricated from both alloy and SL material, and will soon be tested for spectral response and quantum efficiency at FIR wavelengths

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